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Review

Sustainability Assessment and Engineering of Emerging Aircraft Technologies—Challenges, Methods and Tools

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Abstract: Driven by concerns regarding the sustainability of aviation and the continued growth of air traffic, increasing interest is given to emerging aircraft technologies. Although new technologies, such as battery-electric propulsion systems, have the potential to minimise in-flight emissions and noise, environmental burdens are possibly shifted to other stages of the aircraft's life cycle, and new socio-economic challenges may arise. Therefore, a life-cycle-oriented sustainability assessment is required to identify these hotspots and problem shifts and to derive recommendations for action for aircraft development at an early stage. This paper proposes a framework for the modelling and assessment of future aircraft technologies and provides an overview of the challenges and available methods and tools in this field. A structured search and screening process is used to determine which aspects of the proposed framework are already addressed in the scientific literature and in which areas research is still needed. For this purpose, a total of 66 related articles are identified and systematically analysed. Firstly, an overview of statistics of papers dealing with life-cycle-oriented analysis of conventional and emerging aircraft propulsion systems is given, classifying them according to the technologies considered, the sustainability dimensions and indicators investigated, and the assessment methods applied. Secondly, a detailed analysis of the articles is conducted to derive answers to the defined research questions. It illustrates that the assessment of environmental aspects of alternative fuels is a dominating research theme, while novel approaches that integrate socio-economic aspects and broaden the scope to battery-powered, fuel-cell-based, or hybrid-electric aircraft are emerging. It also provides insights by what extent future aviation technologies can contribute to more sustainable and energy-efficient aviation. The findings underline the need to harmonise existing methods into an integrated modelling and assessment approach that considers the specifics of upcoming technological developments in aviation.

Keywords: aviation; sustainability assessment; life-cycle engineering; environmental analysis; socio-economic analysis

1. Introduction

The contribution of the aviation sector towards climate change has increasingly gained attention over the past years, given the continued growth in passenger air traffic and transportation of goods. The aviation sector accounts for around 2.5% of the global energy-related CO_2 emissions [1] and is also responsible for a variety of non-carbon related emissions contributing to the radiative forcing (RF) of the climate system [2]. Despite the continuous improvements in aircraft technology, fuel efficiency, and more efficient operational procedures, total aviation emissions are increasing due to the fast growth in global air traffic demand [3,4]. While efficiency improvements are expected to reach rates up to 1.5% annually, forecasts indicate an average annual growth of air traffic demand of about 4.5% [5]. In contrast to road transportation, the long lifetime of aircraft (20–30 years) implies doubling or tripling of aviation-induced CO_2 emissions until 2050 unless radical changes are made [6]. Furthermore, the aviation sector is criticised for various other impacts, such as noise emissions, especially in the vicinity of airports [7].

In order to significantly reduce the environmental impacts from aviation and to achieve the CO_2 targets derived from the commitments in the Paris Agreement and emission-reduction goals of Flightpath 2050, efficiency improvements of conventional aircraft technologies are not sufficient. On the other hand, novel technologies, such as electric or hybrid-electric propulsion systems, have the potential to enable more sustainable and energy-efficient aviation. Here, conventional kerosene-based jet engines are replaced by battery-powered, fuel-cell-based, or hybrid-electric propulsion concepts, which reduce or eliminate in-flight greenhouse gas (GHG) emissions [6,8]. Besides, alternative jet fuels, that are produced from bio-feedstocks [9,10], as well as so-called electrofuels (e-fuels) that are synthesised using renewable energy sources (RES) [11,12], are discussed as promising options to replace fossil-based kerosene as an energy carrier. Furthermore, lightweight strategies have been explored and developed to reduce aircraft weight and, consequently, fuel consumption [9].

While the novel technologies can help to reduce the in-flight emissions during the use stage of an aircraft, the environmental impacts are potentially shifted to other life cycle stages, such as raw material extraction, production, or end-of-life (EoL). This might also imply essential changes in the global material and energy flows linked to this sector. As known from the automotive industry, the provision of materials for batteries is linked to energy-intensive processes associated not only with the release of GHG emission but also many other environmental impacts [10]. Moreover, the economics of novel aircraft technologies need to be considered. For example, electric aircraft are potentially less expensive to operate as they require less maintenance and repair, and electricity as an energy source is less expensive than kerosene. However, production and recycling might be more expensive compared with conventional aircraft powered by kerosene-based jet engines [11].

Additionally, social issues might arise in the early stages of the life cycle. For example, the batteries that are used in electric aircraft consist of critical and rare materials that are partly mined in developing countries with high risks of corruption, child labour, and poor working conditions [11]. Similarly, the cultivation of suitable feedstocks for the production of biofuels competes with food production and could lead to problems with local communities [12].

Within this context, the sustainability of emerging aircraft technologies needs to be assessed from a life cycle perspective. For this purpose, a framework for the modelling and assessment of sustainability aspects of future aviation technologies is introduced, serving as the basis for a structured literature review. It provides an integrated consideration of aircraft technologies, sustainability dimensions and indicators, assessment methods, life cycle stages, as well as the necessary management of multidisciplinary (research) data. In this way, a holistic sustainability assessment considering the particularities of upcoming technological developments in aviation can be provided.

Such a framework has not been yet introduced in the literature and most of the available studies address single aspects of sustainability, or only selected technologies. Thereby, a current and complete overview of these studies is still lacking. This paper aims to address this research gap by providing a structured review of the methods and tools for the assessment and engineering of future aircraft technologies. This structured overview determines which aspects of the framework are already well addressed in research and where further investigations are still needed.

The remainder of this paper is structured as follows. The framework for the modelling and assessment of sustainability aspects of future aircraft technologies is introduced in Section 2, also presenting methods and tools available for modelling the future of aviation. Based on this framework, the review methodology and meta results are described in Section 3. This is followed by an overview of the selected papers for the literature analysis, dealing with life-cycle-oriented analysis of conventional and emerging aircraft propulsion systems in Section 4. At this point, a first aggregated descriptive analysis of the corresponding articles in terms of technologies for a more sustainable aircraft propulsion system, sustainability dimensions and indicators, and assessment methods is presented. With the focus on the research questions defined within the framework in Section 2, detailed analyses of the article-clusters are carried out and presented in Section 5. Most important and innovative findings from the literature analysis, promising approaches, and research needs are identified in Section 6. Conclusions and outlook are presented in Section 7.

2. Framework for Sustainability Modelling and Assessment of Emerging Aircraft Concepts and Propulsion Systems

From the 'Our common future' report from the 'Brundtland Commission', sustainability is understood as a way today's generation should live so as not to compromise the living standards of future generations. Often referred to as the triple bottom line, sustainable development is traditionally defined in its three dimensions (*environmental, economic and social*). Against the relative sustainability definition, the concept of absolute sustainability has been reinforced in recent years, considering social and economic dimensions nested inside the environmental dimension. Broadening the scope to all three pillars of sustainability, the Life Cycle Engineering (LCE) concept has been defined "as sustainability-oriented product development activities within the scope of one to several product life cycles" [13]. In this way, the LCE concept aims at guiding engineering activities from the cradle to the grave towards sustainability.

In the context of the current transformation of the air transport system towards new aircraft technologies, sustainability aspects in each of the life cycle stages will determine the success of future aircraft systems and influence their potential to reduce their environmental impact. Figure 1 introduces a framework for an integrated sustainability modelling that enables an efficient assessment and engineering of the product system and its interaction with the related background systems and the spatial context.

In this section, the sustainability aspects and modelling tools to integrate multi-scale physical and environmental, socio-economic models for assessing the future of aviation are introduced. The need for an integrated LCE modelling approach, enabling the development of a large number of inventories based on the variation of technical, geographical, and temporal parameters, is justified, allowing a robust sustainability assessment of the future development of aviation. As seen in Figure 1, the framework brings together three blocks of models and functions in an integrated modelling and analysis platform. It contains libraries of models depicting the possible foreground and background systems (cf. *Data models*) as well as models to describe the interaction between the background and the foreground system and their modelling (cf. *Life cycle modelling and engineering*). The integrated framework is linked furthermore to models for the evaluation of the product system in terms of socio-economic and environmental impacts and data analytics procedures that enable the integration of this key performance indicators as engineering constraints in the development of these technologies (cf. *System analysis*).

In the following, each section of the framework is described, and its relevance for the sustainability assessment and engineering of future aircraft technologies is justified. Following the introduced framework, the research questions that need to be addressed are derived.

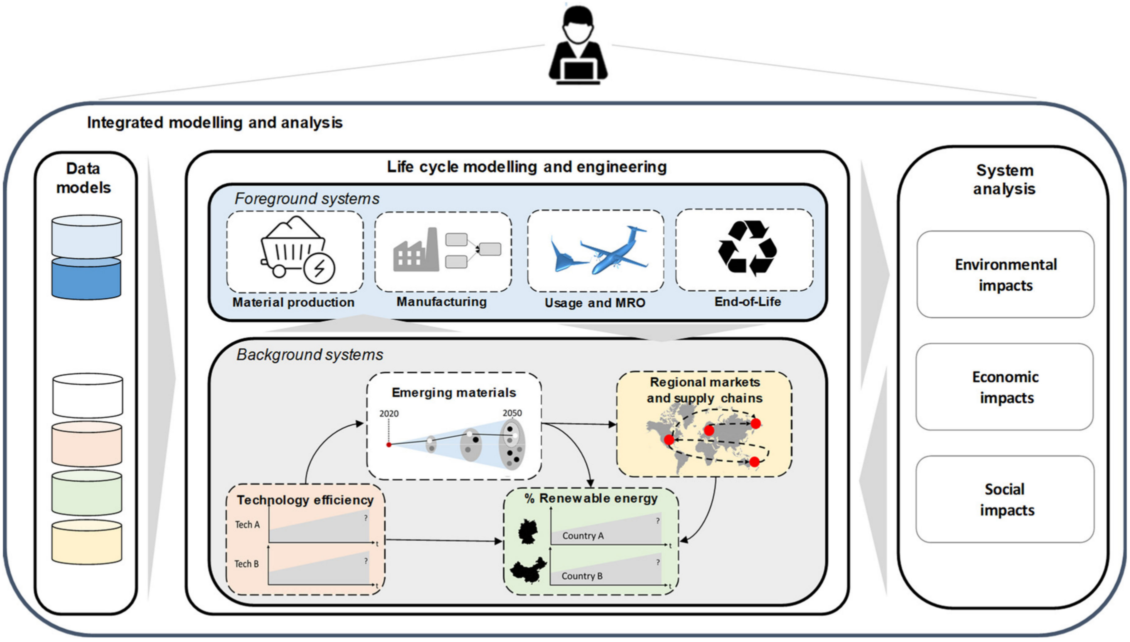

Figure 1. A modelling approach for the sustainability assessment and engineering of future aircraft systems.

2.1. Data Models

The sustainability assessment and engineering of complex systems, such as an aircraft, require a substantial amount of data (i.e., facts without context). Due to the rapid digitalisation, an increasing quantity of data with significant value for engineering purposes is available [14]. For example, for the sustainability-related engineering of an aircraft, data describing the air traffic system, the single aircraft, and involved technologies, as well as cost structures and environmental impacts at various levels of detail and across the whole life cycle, need to be considered. Since data serve as a basis for modelling the foreground and background system, it needs to capture all relevant sustainability-related flows (e.g., material, energy, costs) employed throughout the entire life cycle of aircraft systems and the systems in the background. Thus, data need to be available for the foreground and the background systems.

Foreground data models refer to the processes related to the system under consideration concerning its whole life cycle (i.e., repositories of experimental results from measurements, simulations, calculations, or reports regarding materials, components or processes, industry-specific data, or company internal data). Looking into batteries, considering the different processes for the production lines (e.g., processing electrodes: dispersing, formulation, coating, drying, and calendaring), the process strategies and parameters can strongly influence the energy density of the cathode and the performance of the battery, as investigated for the case of sulfur batteries [15]. In this way, in order to model the foreground processes related to the battery technology involved, understanding the interactions between battery cell production technologies, material and process parameters, and product properties are necessary. Plenty of discipline-specific models for aviation technologies are being developed. For the sake of sustainability modelling and engineering of future aircraft systems, these models can provide a robust scientific base to understand these technologies and can be coupled and integrated into multi-model platforms.

Background data models comprise all data which are suited to define scenarios, e.g., for the surrounding conditions (i.e., technology developments, regional-specific data such as the origin and composition of a particular material, energy mix, geographical data, or socio-economic data) [16]. In this way, data needs to be collected for building a life cycle inventory (LCI) required for the evaluation of future aircraft technologies and quantification of their impacts, investigating how these technologies will develop in the following years, in terms of efficiency, material requirements and production processes, for instance.

The structuring of foreground and background data is a necessary step so that it can be aggregated to sustainability-related information, i.e., data with context, and so that this information can be further aggregated to knowledge in the system analysis to define context, patterns, correlations, causations, or inform standards [14]. In this regard, data models provide the required underlying structure of a database. By using data models, sustainability-related data can be organised in such a way that it supports life cycle modelling of foreground and background systems and, finally, the system analysis of future aircraft systems.

2.2. Life Cycle Modelling and Engineering

Based on the aforementioned foreground and background data models, parameterised LCI models are created, so that upscaling the investigated technologies depending on the configured system is possible. From the developed parameterised models, a life-cycle-oriented assessment model can be built to quantify the environmental and socio-economic impacts (cf. *System Analysis*). Encompassing reliable data models, modelling routines can be integrated into a computational architecture in order to compute the impacts, as introduced by Cerdas et al. [16] for the case of electric vehicles. Through the additional use of Visual Analytics, results can be interpreted supporting decision-making.

Integrated modelling can take place at different levels of interest (e.g., component, aircraft, and system-level). At a system level, aircraft technologies should be assessed in a long-term horizon, considering the transformation of the power generation towards renewable energies, and the different ownership models, including commercial, private, and emerging concepts of on-demand air mobility with the so-called electric vertical take-off and landing aircraft (eVTOLs), for example. At aircraft level, different technologies and configurations are coming up in the future, which can be designed for short ranges (e.g., batteries), medium ranges (e.g., batteries and alternative fuels), and long ranges (e.g., enabled by fuel cells). Finally, at the component level, the material composition of aircraft systems can significantly influence the environmental impact (e.g., reducing aircraft operating weight with the use of lightweight composite materials).

Additionally, the impacts driven by the new technological developments in aircraft applications are characterised by a high uncertainty due to the large variability of technical parameters, as well as geographical and temporal variability. In terms of technological aspects, the variability involves how the sustainability implications depend on the technological or technical characteristics related to the vehicle (e.g., comparing the environmental impact of different battery technologies). For the geographical variability, the focus relies on the influences that local characteristics can have on the environmental impacts (e.g., climatic conditions, electricity mix). For example, the energy consumption of eVTOLs depends on climatic conditions and the usage behaviour (e.g., cruise speed, acceleration, comfort requirements, charging behaviour). Also, regional differences in the electricity mix may influence the impacts of future aircraft systems. A mix based entirely on renewable energies most likely leads to a completely different result than a mix based on fossil fuels. As the material and energy flow needed to manufacture, operate, and recycle the aircraft define its life cycle, the same holds for the production of materials used for the aircraft components. A component might be produced in a particular country, but have some raw materials imported from other countries. Due to the different technologies used, the same item produced in different countries may lead to different environmental impacts. Similar aspects are related to temporal contexts. Due to the daily fluctuation of electricity mixes and seasonal renewable energy fluctuation in the electricity mix, results are influenced by daytime and season. Additionally, results particularly represent a specific time context (present or future scenario, e.g., 2020 or in 30 years, 2050).

By addressing the high uncertainty on the variability of input parameters, more robust results can be provided when evaluating emerging technologies in aviation. Since emerging technologies for aircraft also need to be evaluated from different sustainability perspectives, several methods and tools are presented in the following section of the framework.

2.3. System Analysis

The system analysis transfers the life cycle modelling of the foreground and background systems into corresponding environmental, economic, and social impacts. Depending on the goal and scope of a research study, suitable environmental, economic, and social assessment methods, as well as methodologies focusing on the assessment of multiple criteria, can be used. By encompassing all three pillars of sustainability within the ISO 14040 methodological framework, the Life Cycle Sustainability Assessment (LCSA) methodology enables the evaluation of environmental, economic, and social issues [17]. Within LCSA, environmental and socio-economic indicators along the life cycle of a product can be analysed, and their impact can be assessed in the scope of the same system boundaries. However, some methodological challenges are associated with the implementation of LCSA. The quantification of social data and its correlation to the functional unit, the availability of data in a life cycle perspective, the choice of indicators are some of the difficulties in its operationalisation [18]. Additionally, the definition of system boundaries and the development of methods for sensitivity and uncertainty analysis are challenges needed to be addressed to assess sustainability through LCSA.

In general, several methods and tools are available that can support the evaluation of the sustainability performance of technologies in aviation. These can be grouped into environmental, economic, and social assessment methods.

2.3.1. Environmental Assessment Methods

Regarding environment-oriented assessment methods, the well-established methodology for system analysis, the Life Cycle Assessment (LCA), enables the evaluation of environmental impacts of product systems throughout its entire life cycle. This methodological framework has been widely acknowledged by industry and governmental bodies worldwide as the most robust methodology for the consideration of environmental impacts of products for the following reasons: (i) it provides a robust framework to analyse a product system considering all of the life cycle stages, (ii) the methodology is based on scientific foundations such as mass and energy conservation laws as well as validated empirical models, and (iii) it offers quantitative results which make decision-making less complicated and can be implemented within engineering development activities.

LCA is an ISO standard method and is composed of four phases: goal and scope definition, LCI, life cycle impact assessment (LCIA), and interpretation. In the LCIA phase, the inventory of emissions compiled in LCI is classified and characterised in distinct environmental impact categories [19]. However, high amounts of resources and time (e.g., for data collection and creation of LCIs) and expert knowledge are usually required in LCA, affecting the widespread acceptance of the methodology to support engineering decisions. In addition to the significant modelling efforts, other aspects related to data uncertainty and high variability of parameters (cf. *Life cycle modelling and engineering*) hinder the applicability of LCA for decision-making support in engineering. Aiming to support a robust evaluation of future aircraft technologies, an LCE modelling approach based on coupled multidisciplinary models (cf. *Data models*) will contribute towards enhancing the understanding between the technical properties of the system, its elements, and the resulting impacts. Besides full LCA, simplified evaluation approaches exist, which focus on the evaluation of single environmental aspects such as climate change or water scarcity. Examples are the carbon footprint or water footprint methodologies [20].

2.3.2. Economic Assessment Methods

Concerning the economy-oriented assessment, several methodological approaches exist for the calculation of costs and performance [20]. Consistent with LCA, the Life Cycle Costing (LCC) methodology quantifies the economic aspects along the entire life cycle by aggregating all costs and benefits associated with the product under analysis. By doing so, potential economic hotspots can be identified. For the assessment based on LCC, the Society of Environmental Toxicology and Chemistry (SETAC)—Europe Working Group on Life Cycle Costing defined three types of LCC which differ in the scope of the external costs to be taken into account: conventional LCC, environmental LCC, and societal LCC [21]. In conventional LCC, all costs associated with the product life cycle that are directly covered by the producer or user are assessed. The approach is focused on internal costs. These are all costs on which a company bases its price. They include costs such as materials, energy, labour, plant, equipment, and overheads. Using conventional LCC, a product is analysed from the perspective of one market actor (manufacturer or customer) and is usually not accompanied by separate LCA results [21]. In environmental LCC, all costs within the life cycle of a product that are covered by one or more market actors (supplier, manufacturer, consumer, or EoL-actor) are assessed. The societal LCC extends the environmental LCC by additional assessment of further external costs, usually in monetary terms (based on willingness-to-pay methods). The perspective of the analysis is from the overall society, national, and international, including governments [21]. Other approaches like eco-efficiency [22], techno-economic assessment [23] as well as input–output analysis [24] enable the quantification of environmental impacts with economic parameters.

2.3.3. Social Assessment Methods

To analyse the social consequences of products or processes on society, the Social Life Cycle Assessment (SLCA) is a comprehensive method for the social assessment, integrating social and socio-economic criteria into the LCA [25]. The basis of an SLCA are subcategories that are related to different stakeholder groups via impact categories. These subcategories are socially significant themes or attributes, such as child labour, working conditions, corruption, or salary. They are classified into impact categories, such as human rights, health and safety, or socio-economic repercussions. The purpose of the classification into impact categories is to classify subcategories within groups that have similar impacts, which supports a structured impact assessment and interpretation by the stakeholders. The stakeholders are various actors within a society such as the local community, consumers, workers, or the society itself, which are affected by social impacts along the product life cycle.

All these methodologies take up all relevant life cycle data and models and, using appropriate calculation modules, determine the corresponding impacts resulting from the modelled system. The results of the system analysis can be used to acquire knowledge of the performance of aviation technologies. Thus, potentials for the reduction of a specific impact can be identified. With these potentials, engineering measures can be derived which aim to reduce a specific impact. Therefore, these measures can be virtually implemented in the life cycle modelling and, in interaction with the system analyses, also be evaluated. In such a way, LCE can be conducted, which aims to improve desired or reduce undesired environmental, economic, and/or social impacts over the whole life cycle.

This presented framework is the basis for the modelling and assessment of emerging aircraft concepts and propulsion systems. In the following, a structured literature analysis is used to determine the already well-addressed aspects of the presented framework in the scientific literature and to identify research needs. For this purpose, the following research questions are derived and will be answered: Which aspects of the presented framework are already addressed in the scientific literature? Which approaches are applied in the literature for assessing the sustainability of future propulsion systems in aviation? In which areas is there still need for further research?

In order to address these questions, the methodology of the structured literature analysis is presented in Section 3. The scope of the analysis is shown and the search strings used are defined. Subsequently, an overview and classification of results of the structured literature analysis is briefly presented in Section 4, followed by a detailed analysis of all articles identified that deal with the life-cycle-oriented analysis of conventional and future aircraft in Section 5.

3. Review Methodology

Against the context of the introduced framework and the defined research questions, a review methodology is applied in order to address the objective of this paper.

A systematic search procedure was applied to ensure comprehensiveness and to minimise the risk of bias in selecting relevant articles. Based on the research questions of this article defined in Section 2, appropriate keywords were identified and combined into two multilevel search strings that specify the context and the subject of the items. The structure of the search string is illustrated in Figure 2. The search string A includes keywords that are related to the context (Life Cycle/Sustainability) (Assessment/Analysis/Evaluation) and the subject (Aircraft/Aviation/Airplane). It is complemented by the search string B with the context (Multidisciplinary/Interdisciplinary) (Data) (Modelling/Management) for the same subject to reflect the increasing relevance of multidisciplinary data in sustainability analysis and evaluation. The searches were carried out in November 2019 using Elsevier's Scopus database (www.scopus.com), which provides extensive coverage of peer-reviewed scientific literature and offers an advanced interface for detailed analysis and data export [26,27].

The results from the database search were analysed in a structured screening process. First, formal criteria were applied to include only articles that are available for a more detailed analysis and are written in English. In addition to the articles from peer-reviewed scientific journals, conference papers are included to ensure a sufficient data basis for the analysis of the environmental impact of aviation and the development of the framework addressed in this paper. Second, the abstracts of these articles were analysed concerning content-related criteria. Within search process A, only articles dealing with the life-cycle-oriented analysis of conventional and emerging aircraft propulsion systems are included. Within the search process B, only articles related to the integration of multidisciplinary data models and/or life cycle engineering or management are included. For the items remaining in the database, the full texts were retrieved to extract the relevant information. Additional references that were identified during this step were added to the review database (search processes A-II and B-II), resulting in a total of 47 articles for search process A and 19 articles for search process B. A total of 66 articles are analysed in this contribution.

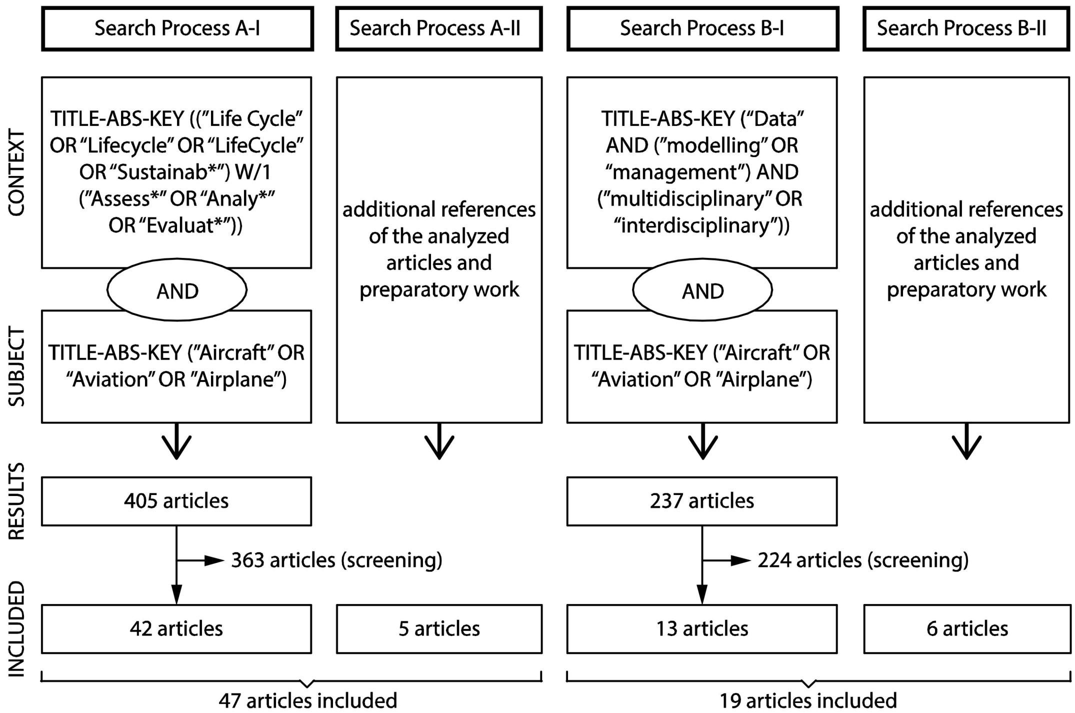

Figure 2. Search strategy and results.

For a first overview, the distribution of the publication output over time is investigated. Figure 3 illustrates the number of articles by publication year. The growth in the number of publications over time reflects an increasing deployment of life-cycle-oriented analysis of aircraft propulsion systems. To increase the environmental performance of the air transport system, aeronautical research programmes (e.g., Clean Sky), were launched in Europe and promoted the development of breakthrough technologies for the next generation of aircraft; hence motivating the development of assessment tools for LCE analyses. In particular, the sustainability assessment of aircraft propulsion concepts has been of interest since 2010, irrespective of achievements of LCA methodologies in the 1990s. Notably, in 2017 and 2018, more research was conducted in this area. This might be related to increasing pressures resulting from the objectives of the Paris agreement, rising kerosene prices, and changes in the legal framework like the European Union Emissions Trading System (EU ETS) and the Carbon Offsetting and Reduction Scheme (CORSIA) [28–30].

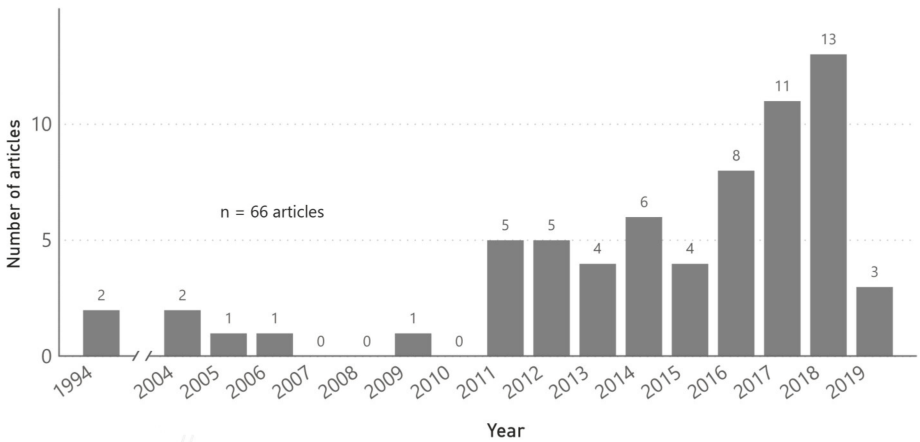

Figure 3. Distribution of articles by publishing year.

For a better overview of the literature investigated, the following section focuses on the classification of the reviewed articles from the search process A, before conducting a detailed analysis of the review database in Section 5. The descriptive analysis of articles is carried out according to the mentioned technologies for a more sustainable aircraft propulsion system, the sustainability dimensions and indicators investigated, and the assessment methods applied.

4. Descriptive Analysis of the Selected Literature

In this section, a first descriptive analysis of the selected literature of search process A regarding the technologies considered, the sustainability dimensions and indicators used, and assessment methods applied is conducted. By doing so, a first structuring and characterization of the literature is provided, which is the preliminary work for the more detailed analysis in Section 5.

4.1. Technologies for a More Sustainable Aircraft Propulsion System

Given the need for decarbonising the aviation sector, research in the field of novel propulsion concepts has been intensified in recent years. This research usually addresses a conventional jet engine, which causes less climate-damaging emissions through improved combustion processes and increased efficiency. Fuel is used as an energy source, whereby efforts are made to reduce the reliance on fossil kerosene. In particular, biofuels based on vegetable feedstocks and e-fuels such as hydrogen, which is obtained via power-to-fuel (PtF) processes, are potential alternatives to fossil kerosene. In addition to research in the field of novel fuels, electric and hybrid-electric propulsion concepts have been addressed in the last 5–10 years. These concepts use electricity as an energy source and can reduce or completely avoid dependence on fuels. The electricity is either provided by a battery system or is generated by a fuel cell.

In the literature investigated, conventional propulsion systems based on different fuels are mainly addressed. Figure 4 shows how often different technologies are considered. Multiple assignments are possible, for example, when comparing biofuel with fossil kerosene. More detailed analysis of raw materials (e.g., feedstocks) and extraction processes are discussed in the following Section 5. For electrified concepts, the technology for providing electricity is used as a reference. Due to the small number of articles dealing with electrified propulsion concepts, the generic terms 'Battery' and 'Fuel Cell' are used. Further details regarding the specific type of technology (e.g., lithium-ion battery) is unnecessary and not helpful here. Considering that eVTOLs are not within the scope of this paper, batteries as a potential technology for sustainable aviation, are examined only in a total of two articles. In contrast, the sustainability of fuel cells systems for aircraft has not been addressed in the scientific literature so far.

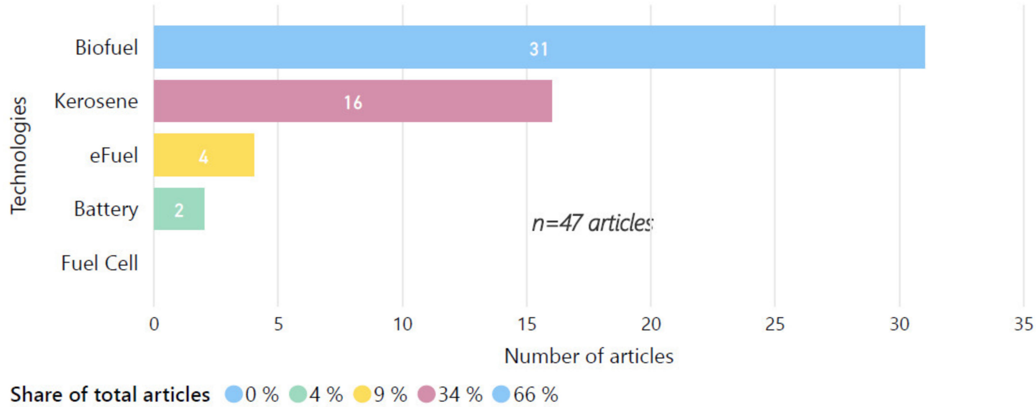

Figure 4. Distribution of articles by considered technologies for sustainable aviation.

4.2. Sustainability Dimensions and Indicators

As aforementioned, the classification and evaluation of articles based on the sustainability dimensions and indicators refer to the traditional understanding of sustainability according to the 'Brundtland Report'. Due to this report, sustainability is determined based on three dimensions: the environmental, the economic and the social dimension. Further detailing based on the United Nations 'Sustainable Development Goals' or the consideration of temporal components such as the duration of usability is neglected here, because in any case, one or more of the three standard dimensions of sustainability is addressed. As illustrated in Figure 5, out of 47 articles analysed, only one addresses all three dimensions of sustainability simultaneously. Environmental aspects receive most of the attention (45 articles), followed by economic (17 articles), and social (3 articles) dimensions.

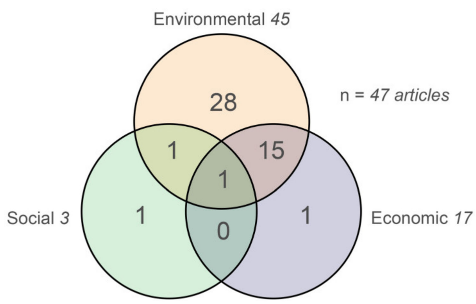

Figure 5. Distribution of articles by considered sustainability dimensions.

Figure 6a shows the impact categories (here referred to as indicators) that are used to assess the environmental dimension of sustainability within the system analysis section of the framework. The most commonly used categories are climate change and land use, addressed in 73% and 16% of the 45 articles, respectively. GHG emissions from alternative fuels during operation are often investigated in comparison with fossil-based kerosene. Figure 6b shows the indicators that are used to assess the economic dimension of sustainability. These are indicators that quantify the economic performance of future aircraft systems. Cost-oriented indicators are mostly investigated, followed by price-oriented indicators. In addition, revenue-oriented indicators, as well as the net present value, are analysed by some authors. Concerning the social dimension of sustainability, it is challenging to identify frequently occurring indicators. Well-known indicators such as fair salary, child labour, human rights, working hours, or social security are not explicitly mentioned in the investigated articles. Rather, the influence on individual groups of the society is described, which can be assigned to the stakeholder categories of the SLCA. These are the 'local community', 'workers', 'consumers', and 'society'. Figure 6c shows the four groups of stakeholders that are addressed. The stakeholder categories 'local community' and 'workers' are each addressed in two articles, while 'consumers' and 'society' are considered in one article. However, a more detailed analysis of the social sustainability assessment is complicated, as only three of the articles selected for this review take the social dimension into account at all. This could be due to the fact that in the past, primarily environmental and economic indicators were of interest. While political decision-makers define guidelines and laws mainly based on environmental parameters and airlines or manufacturers make decisions based on economic indicators, social indicators have often been neglected. However, a social analysis will become increasingly important in the future. Since environmental and economic indicators are already being analysed in detail, social criteria will be used more frequently in decision-making in the future, which makes social analysis relatively more important.

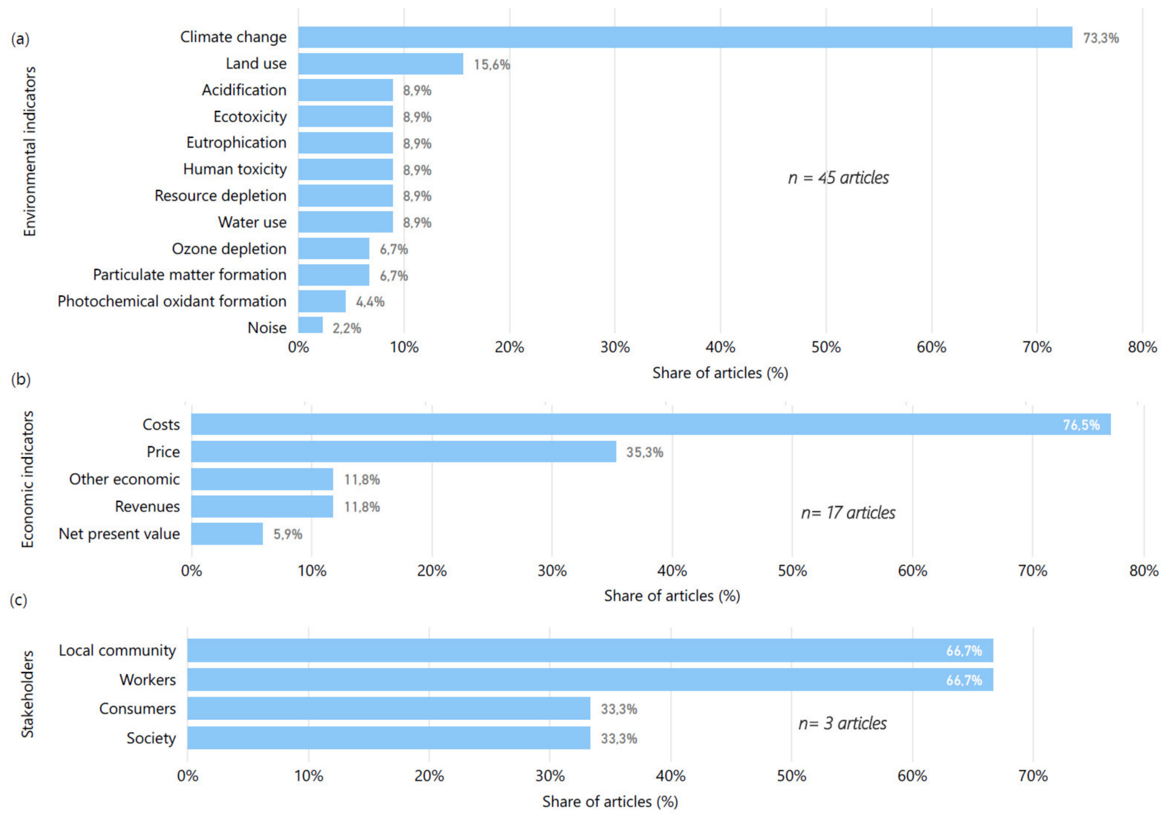

Figure 6. Distribution of articles by indicators from environmental (**a**); economic (**b**); and social (**c**) sustainability dimensions.

4.3. Assessment Methods

The methods are primarily structured according to the sustainability dimension addressed (see Section 4.2). Within the environmental, economic, and social dimensions, the methodology chosen is further detailed. In addition, methods for multi-criteria assessment are presented. These approaches especially focus on decision support through the assessment of indicators from different sustainability dimensions. This also includes the integrated approaches of techno-economic assessment and LCSA.

As illustrated in Figure 7, the most commonly used method for evaluating the impacts of future technologies in aviation is LCA (83% of the reviewed papers). Besides LCA, other methods have been used to evaluate the environmental and/or socio-economic impacts of aviation. Examples are LCC, SLCA, LCSA, or multi-criteria decision analysis (MCDA). Several studies used methods that consider only single indicators of the environmental, economic, or social dimension, such as the internal rate of return, carbon footprint, or eco-efficiency. All of the methods, except for LCA, have been used in not more than three of the analysed articles.

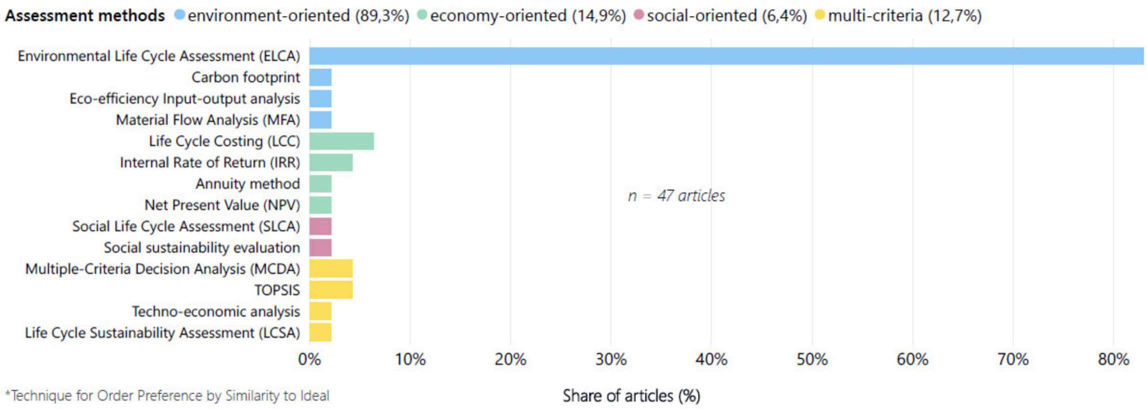

Figure 7. Distribution of reviewed articles by environment-oriented, economy-oriented, social-oriented and multi-criteria assessment methods.

In order to derive answers to the specific research questions defined in Section 2 and to identify the research gaps in this field, detailed analyses of the 66 selected articles in the review database are conducted. In the following Section 5, the main findings related to the management of multidisciplinary data and to LCE and system analysis are reviewed, in relation to the main components of the introduced framework. Key insights are critically reviewed so that answers to the research questions can be derived, and future research directions can be further identified.

5. Detailed Analysis of the Articles and Key Insights

In this section, the selected literature is analysed regarding the main components of the introduced framework. As discussed in Section 2, given the need for LCI datasets to assess the environmental impact of emerging aircraft technologies, comprehensive and reliable multidisciplinary data models play an essential role in ensuring robust LCA results [31]. In this way, methods that support the management of multidisciplinary data have gained relevance in the field of sustainable aviation. To address this topic, the management of multidisciplinary data models is analysed in Section 5.1. Section 5.2 covers the life cycle modelling and system analysis, starting with an overview of the assessment of current impact of aviation, the life cycle stages, and systems boundaries, followed by a literature analysis according to the different emerging technologies for more sustainable aviation.

5.1. Management of Multidisciplinary Data

The collaboration of specialised engineers, the seamless integration of disparate cyber-physical systems, and transparent interoperable modelling and management of heterogeneous data in multidisciplinary research environments are key challenges for the assessment and engineering of emerging aircraft technologies [32]. Therefore, the increasing relevance of multidisciplinary data in sustainability analysis is reflected by the separate search string B, as mentioned in Section 3.

Different approaches have been developed in the past that capture these challenges. The approaches comprise among other things such as software programs [33], multidisciplinary design and analysis

(MDA) environments (e.g., [32,34–37]), multidimensional frameworks to enhance collaboration and synchronisation between separated disciplines [38], as well as processes to support multidisciplinary virtual design and assessment [39]. Current research fosters the realisation of highly integrated, multidisciplinary design environments [40]. These must reflect the inherent interdependencies of data and support its handling and utilisation, as well as structured knowledge pooling across various layers of interest and involved actors from multidisciplinary backgrounds [40,41].

Effective data management supports these holistic multidisciplinary approaches by providing faster and more efficient knowledge acquisition. Therefore, a common data language is required and can be considered one of the four main components in a collaborative design process, besides engineering routines, a process integration framework, and methods for collaboration. Standard data model(s) lay the groundwork for multidisciplinary and multilevel sharing of data in engineering networks and between their involved engineers [41]. They refer to the "collection of conceptual tools for describing the real-world entities to be modelled in the database and the relationships among these entities" [42].

Different articles take over the increasing demand for standard data models. Lin and Afjeh [43] develop and implement an XML-based data object model for multidisciplinary aircraft design. One of the most common and popular data models in the aviation sector is the Common Parametric Aircraft Configuration Scheme (CPACS), as developed by Nagel et al. [44,45]. CPACS is a unified open central data model to support collaborative research in aircraft design and features a hierarchical data structure. It serves as the standard language for the communication between multiple, decentralised, and heterogeneous partners in designing air transport systems, such as aircraft. CPACS has been widely used and further developed for a different design and engineering purposes in the aviation sector (e.g., [14,46–48]). Besides the modelling of data using standard data models, data quality is also considered since it has an essential influence on the quality of engineering decisions. In this regard, Li and Ryerson [47] review the diversity, availability, tractability, applicability, and sources (DATAS) of aviation research data. Furthermore, Hazen et al. [48] exemplarily explore the outcomes of a data quality improvement process implementation in an operations management environment within an organisation with a large aircraft fleet.

The next section focuses on the analysis of the framework component *Life cycle modelling and engineering* and *System analysis*. Due to the general limitation of available literature, no explicit differentiation between foreground and background systems can be made. Instead, the focus of the following subsection lies on giving an overview of the sustainability aspects. The focus here is on the system boundaries and the significance of particular life cycle stages when assessing the impact of conventional aircraft, followed by a literature review on potential technologies for more sustainable and energy-efficient aviation, as suggested in the scientific literature.

5.2. Life Cycle Modelling and System Analysis Towards a More Sustainable Aviation

Looking into future technologies in aviation means different system boundaries and that new environmental impacts might gain relevance. Although emissions from aircraft operation can be significantly decreased (e.g., by reducing the weight and consequently the fuel consumption through the use of composite materials), a problem shifting to other life cycle stages or impact categories might shift the relevance of the operation phase to the extraction of raw materials or increase the influence of the energy supply chain, for instance. Hence, assessing the real improvement potential of future technologies in aviation consists in revealing the environmental hotspots and the interactions with socio-economic perspectives.

In this way, results are sensitive to the system boundaries defined at an early assessment stage. Based on specified boundaries, unit processes in a product life cycle can be included or not, depending on their relevance to the purpose of the study. Figure 8 shows the life cycles and the different perspectives of the system boundaries for the assessment of aviation. Not only the whole aircraft life cycle should be assessed, but also the environmental burdens of related processes need to be accounted for in order to conduct a complete evaluation of the environmental impacts of aviation. This includes the well-to-wake life cycle for fuel (WTW) and the life cycle of the necessary infrastructure (airport), as depicted in Figure 8.

From Figure 8, the main life cycle stages for assessing the current environmental impact of aviation are found. The production of the aircraft starts with resource extraction, component manufacturing, and its final assembly. The aircraft operation implies fuel combustion, energy consumption as well as maintenance, repair, and overhaul (MRO) activities. The fuel production covers its extraction, refining, and transport, while the infrastructure life cycle considers all impacts associated with airport construction, operation, and EoL. Finally, the aircraft EoL includes all impacts associated with its disposal treatment, such as recycling.

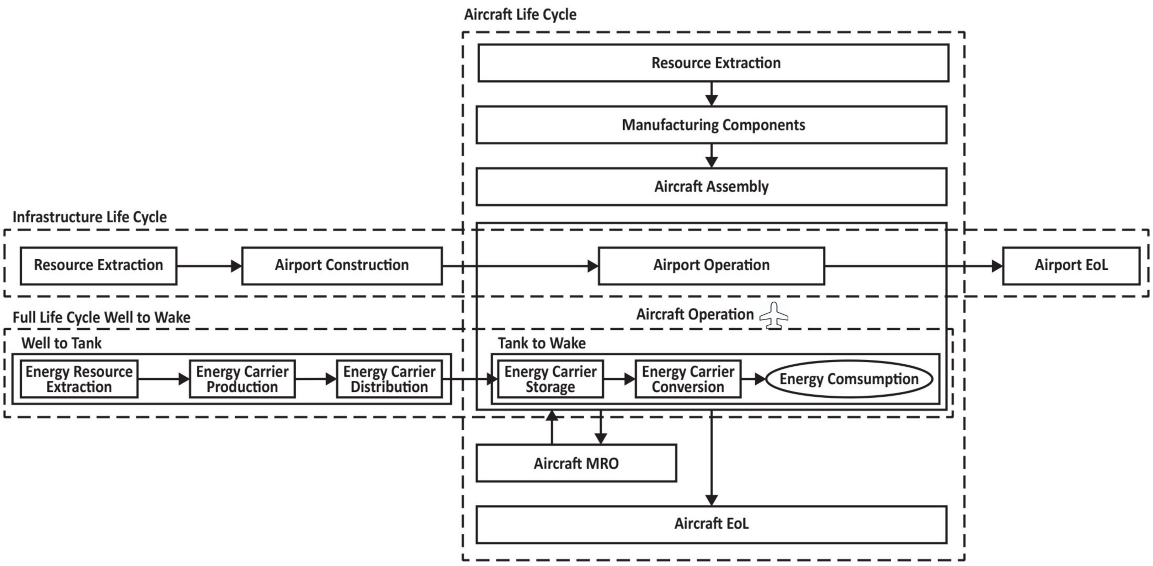

Figure 8. Life cycles and system boundaries for sustainability assessment of aviation.

While environmental impacts from aircraft operation are caused due to fuel consumption during flight operation, modelling the environmental burdens from a ground operation, take-off, and landing consists in accounting for local noise and emissions. Sources are, for instance, auxiliary power units, ground handling equipment as well as fuel burn emissions from shuttle services at the airport.

Concerning the global warming potential (GWP), three articles in the literature investigated more closely the GHG emissions in the individual life cycle phases of an aircraft. In the articles, a total of seven scenarios is defined in which the GWP of different aircraft types is analysed along their life cycle. The types of aircraft are distinguished as follows: regional (REG), narrow-body (NB), and wide-body (WB). While REG refers to an aircraft with a seating capacity of around 50 and a flight distance of typically 300 km, NB refers to a 125 (small NB) and 200 (large NB) seating capacity and is designed for medium distances (up to 4000 km). With two aisle configuration, WB has a seating capacity of around 440 (small WB) to 620 (large WB) and is typically used for longer flight distances (up to 10,000 km) [49].

As shown in Figure 9, the aircraft operation accounts for the highest contribution to the GWP, from 77% [50] to 91% [49], not including the fuel production. Johanning et al. [51] consider only the operation contribution (89%) since the other life cycle stages were not differentiated. For the manufacturing stage, the results vary from 1.48% for NB to 7.5% for WB aircraft [50]. Regarding infrastructure share, including its construction, operation, and EoL, the results range from 0.397% [49] to 5.41% [50] for WB aircraft. Aircraft EoL was either neglected or included in the manufacturing stage. As the second-largest contributor to GWP, the fuel production accounts for 8% (WB) [49] up to 11.85% (NB) [50].

Hence, the contribution of aviation to GWP is mainly driven by aircraft operation and fuel production from crude oil, which is associated with high environmental burdens. According to Koroneos et al. [52], in the fuel life cycle, acidification is the most crucial impact category, followed by the greenhouse effect. Summer smog and eutrophication are also relevant in fuel production; however, having a smaller effect. The combustion of fossil kerosene gives the highest contribution to GHG emissions (99.5% of total CO_2 emissions) and acidification effect (96.04%). By neglecting the use stage, the refining is the most polluting process due to its high energy intensity and high content of sulfur in the process flows. At a lower level, extraction and transportation of crude oil and kerosene give an equal contribution to the environmental impacts of fuel's life cycle.

In this context and driven by the pursuit of more sustainable aviation, the development of alternative jet fuels has been seen as a key strategy to mitigate fuel depletion and GWP impacts in the near future. An advantage is that existing equipment, such as engines and tanks, can be used for alternative fuels. Various production pathways exist towards alternative fuels, distinguished by different energy sources, types of feedstocks, and conversion technologies [53]. In the last few years, much attention has been given to pathways based on biogenic raw materials, the so-called biofuels, or renewable jet fuel (RJF), addressed in the following section.

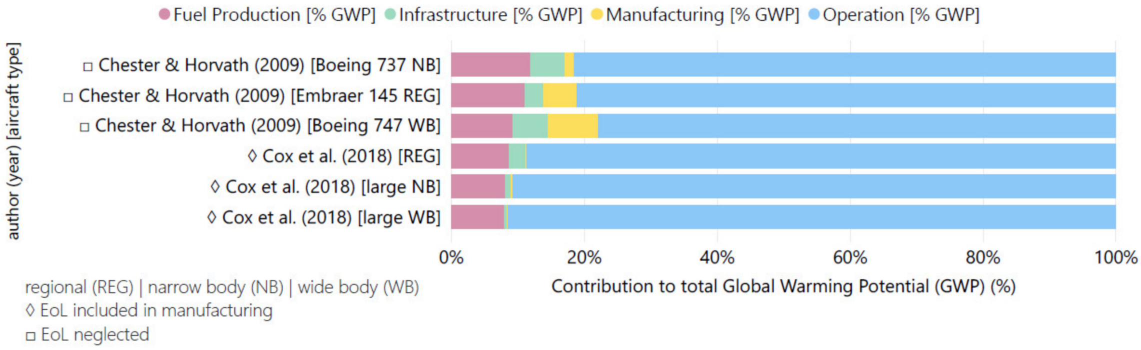

Figure 9. Contribution of life cycle stages to the Global Warming Potential (GWP).

5.2.1. Biofuels

Several studies conducted a quantitative analysis of improvements in terms of GHG emissions of biofuels in comparison with fossil-based jet fuel, using a life cycle perspective. Besides quantifying the potential reduction on CO_2 emissions, investigations on the climate impact from non-CO_2 emissions, particularly on the role that varying flight altitude plays on reducing aviation's climate forcing from the formation of contrails, have been introduced [54]. By changing the altitudes (±2000 feet) of less than 2% of the flights, climate forcing of aircraft contrails could be reduced by 59% [55], which combined with more sustainable technologies adoption, would reduce the impact even further.

Following the different life cycle perspectives illustrated in Figure 8, a holistic life cycle analysis of alternative fuels starts with the recovery (in the case of biomass, land use change would be considered) and transportation of the feedstock from the well or field to the production plant. This process is followed by the processing of fuel, its transportation, and distribution to the aircraft tank, and fuel combustion during aircraft operation [56]. Various feedstocks can be used for converting into fuel, for instance, lignocellulosic biomass (e.g., corn stover, switchgrass, and short-rotation woody crops), starch and sugar, vegetable oils and fats [57]. Moreover, different production pathways are approved to generate sustainable jet fuels. Biofuels can be synthesised through gasification followed by Fischer–Tropsch synthesis (FT), pyrolysis (Pyr), hydrothermal liquefaction (HTL), alcohol-to-jet (ATJ), direct sugars to hydrocarbons (DSHC) and hydro-processed esters and fatty acids (HEFA or HRJ) [57]. A review of alternative aviation fuels is conducted by Yilmaz et al. [58].

Among the aforementioned biofuel production technologies, FT jet and Pyr jet fuel from cellulosic biomass and HEFA from oil crops, algae, and waste oil are promising bio-based aviation fuels with the potential to reduce the GHG emissions [59]. Aiming to quantify the potential improvements with the use of biofuels in aviation, Han et al. [59] employed a WTW LCA analysis, which covers from energy resources extraction up to energy consumption in aircraft operation. HEFA from several oil seeds, FT, and Pyr jet from corn stover were analysed. In comparison with petroleum jet, reduction in GHG emissions can be as high as 63% for HEFA fuel, up to 76% for Pyr jet, and 89% for FT fuel from corn stover. As discussed in Section 2, a high variability in the results can be expected among the different production pathways and technologies.

Aiming to compare different routes for RJF production, Klein et al. [60] evaluated HEFA (processing palm, macauba, soybean oils), FT (based on sugarcane or eucalyptus lignocellulosic material) and ATJ (converting isobutanol or ethanol into RJF) pathways integrated with biorefineries in Brazil. While HEFA-based biorefineries yielded the highest production volumes of RJF production, the best economic performance was achieved by FT biorefineries, synthesising RJF at a competitive cost; however, with a low output. It was shown that all production paths lead to a reduction of over 70% in climate change impacts when compared with fossil jet fuel. However, the locally available feedstock, the production pathway, and plant location have a significant impact on the potential of reduction in GHG emissions in Brazil, as shown by the variability of results, following the foundations of the presented framework.

Han, Tao and Wang [61] examined four emerging bio-based jet fuels (ethanol-to-jet from corn and corn stover and sugar-to-jet from corn stover via biological or catalytic conversion). A WTW LCA approach was employed, and it is demonstrated that the feedstock is a crucial factor in the fuel life cycle emissions. For ethanol-to-jet from corn, a reduction in GHG emissions by 16% is estimated, while from corn stover by 73%, in comparison with fossil jet fuel. For sugar-to-jet via catalytic conversion, three H_2 options were investigated. GHG emissions can be reduced in the range of 28–71%, but the reducing potential highly depends on the hydrogen source.

The influence of the biomass feedstock provision on environmental criteria of biofuel production is also addressed by Neuling and Kaltschmitt [62]. Based on technical, economic, and environmental analysis of four different production processes related to a plant in Germany, each consisting of two types of biomass feedstock, it was found that the burdens related to the feedstock provision have a significant impact on the sustainability of the resulting bio-kerosene, regardless of the conversion process.

Bio-synthetic paraffinic kerosene (Bio-SPKs) was evaluated by Lokesh et al. [63] through a life cycle GHG prediction model using LCA with cradle to grave perspective. Camelina SPK, microalgae SPK, and jatropha SPK lead to a life cycle carbon saving of 70%, 58%, 64%, respectively. Although camelina can be seen as the most sustainable option, microalgae, and jatropha can also have a positive impact due to their natural carbon sequestration and waste land reclamation capabilities. In addition, the higher hydrogen content of Bio-SPKs resulted in a 19% reduction of NO_x relative to fossil jet fuel.

The environmental and economic impacts of the production of biofuels are analysed by Capaz et al. [64] and Tao et al. [65], respectively. Capaz et al. investigate the impact of two production processes for biofuel (enzymatic hydrolysis and syngas fermentation) based on sugarcane feedstock. They use an LCA method for the environmental analysis and perform an attributional as well as a consequential approach to analyse the GHG along the life cycle. The environmental results for biofuel based on sugarcane are compared with the results of conventional kerosene. In future research, the authors want to include economic models with costs and sales price as indicators to refine their analysis. This is intended to analyse the cost drivers of the different production processes and determine the influence on the sales price [64].

In contrast, Tao et al. consider economic aspects, including costs as an economic indicator. Next to the direct production costs, the sales price is included as an additional economic indicator. They investigate the production concept of HEFA for jet biofuel. Five different oil feedstocks (camelina, pennycress, jatropha, castor bean, and yellow grease) are analysed concerning their geographic distribution, production levels, oil yield, prices, and chemical composition. The authors indicate that the market oil price is the main cost driver for producers since it defines the production costs to a large extent and is, therefore, decisive for the sales price [65].

Often simplified assessment approaches are used to consider economic aspects, mostly by including cost-related indicators, as developed by Rye and Batten [66]. The authors investigate the environmental potential of microalgae as a secure and environmentally sustainable alternative fuel feedstock for the Australian commercial aircraft fleet. They compare biofuel with conventional Jet-A kerosene based on an LCA analysis and include the direct production cost as an economic indicator for evaluating the competitiveness of the product at the market. The authors point out that the production of biofuels is currently uneconomical, mainly due to high electricity consumption. While the price of Jet-A kerosene is 0.72 US$/L, the production of biofuel incurs electricity costs of 1.45 US$/L. The authors conclude that improvements in the production systems could make biofuel an economically and environmentally viable option.

Crossin [67] and Chao et al. [68] have developed LCA-based approaches to evaluate the potential of biofuels compared to Jet-A kerosene. Both articles focus on an environmental assessment and include costs as a criterion for economic viability. Crossin investigates the potential of biofuel from mallee compared with kerosene using a conventional LCA analysis. He analyses the theoretical value chain in Western Australia and compares the two types of jet fuel concerning GHG and fossil fuel depletion impacts. Next to the reduction of GHG by 40%, the bio-fuel system shows reduced fossil fuel depletion impacts, decreasing from a total burden of US$893.28 per flight to a net benefit of US$55.72 per flight. The author notes, however, that further conflicts may arise concerning the areas under cultivation, but these are not part of his study [19]. Chao et al. investigate the potential of different alternative fuel options on fleet-level under two emission policy schemes, namely the Global-Market Based Measure introduced by the International Civil Aviation Association (ICAO GMBM) and the EU ETS. The authors assess the potential of the fuel options based on GHG as an environmental indicator and costs as an economic indicator. They use a Multi-Actor Life Cycle Assessment (MA-LCA) to include the impact of different actors such as airlines, farmers, and policymakers on the analysis. Through the study, Chao et al. show that the fuel with the lowest emissions does not necessarily have the highest potential. Instead, at fleet-level, fines, and substitutions determined by emission policy schemes influence the potential and attractiveness of fuel variants [68].

Although a significant reduction in GHG emissions is estimated with the use of biofuels, the considered electricity mix plays a significant role, aspect highlighted within the framework, as the production of alternative fuels can demand a high amount of energy. Johanning and Scholz [69] conducted an LCA on the conceptual design of an aircraft powered by a selected biofuel based on microalgae "Auxenochlorella protothecoides", comparing it to a reference aircraft Airbus A320. For the calculation of its environmental impacts, no changes in design parameters were considered, remaining the same as the reference aircraft, replacing only the kerosene production by the alternative fuel production stage. If the fuel production is based on the current European electricity mix, the single score result corresponds to 243% higher environmental impacts compared with the reference aircraft. However, if renewable energies are used for fuel production, a net positive impact is found, which is related to the high amount of CO_2 to be captured by the algae for fuel production.

Biojet fuel viability within the aviation sector of the United States is examined by Agusdinata et al. [70]. The potential reduction in GHG emissions and calculation of costs associated with different life cycle stages are the main focus of this study, identifying their main drivers. Different production pathways and types of feedstock are analysed: oil-producing feedstock (e.g., camelina and algae) and lignocellulosic biomass. Their viability is subject to the oil price and land availability. When the oil price is high, the lignocellulosic biomass is viable, and its supply potential is significantly larger than oil-producing feedstock, whereas, when the oil price is lower, camelina is viable; however, restricted to land availability for its growth. Assuming the high oil price scenario, GHG emissions can be reduced by up to 92% in 2050 using bio-feedstocks, in comparison with the 2005 baseline level.

A more theoretical approach is developed by Collier et al. [71], investigating the value chain for next-generation biofuels. They develop an approach, which combines an LCA method with a scenario-based multiple-criteria decision analysis resilience assessment to analyse environmental and economic sustainability. The presented approach could be used as the basis for an iterative, anticipatory LCA framework, including costs as an economic indicator to support different stakeholder groups.

Moreover, Warshay et al. [72] used the LCA methodology to investigate the energy and environmental potential of hydro-processed RJF produced from the Integrated Seawater Energy Agriculture System (ISEAS) in comparison with kerosene-based jet fuel. ISEAS has an overall positive impact, having a beneficial land use impact, small freshwater consumption, and acting as a long-term sink for carbon. By examining several production scenarios, the investigated biofuel has the potential to emit 38% to 68% less GHG than fossil jet fuel. However, a reduction on this scale is only possible under ideal production conditions and significantly depends on minimising freshwater use and maximising biomass yield. Moreover, the willingness of airlines to buy biofuels at a higher price than conventional fuel is one of the main drivers for a profitable ISEAS.

An interesting approach regarding a more holistic assessment in the sense of LCSA is developed by Jagtap [73], who investigates the environmental, socio-environmental, and economic impacts of using algae-based hydro processed RJF from the year 2020 in all types of passenger aircraft. The author uses an LCA method to determine the environmental impacts and includes a social analysis to investigate the impact on human health, damage to resources, and eco-system quality, which are relevant themes for the local community as well as for the society. Jagtap shows that the use of renewable biofuel reduces the damage to resources by approximately 78%, the eco-system quality by 1–4.5%, and human health by 23–29%. The author also investigates the production costs of the algae-based biofuel and predicts a sales price of US$4.77/gallon. For the fossil kerosene, he forecasts a price of US$3.41/gallon and concludes that the difference of US$1.36/gallon should be covered by the government using subsidies or tax credits to make alternative fuel cost-effective.

Finally, Hileman and Stratton [56] study the main drivers for available alternative jet fuels. Among the potential alternative jet fuel options, synthetic jet fuels, biodiesel, bio-kerosene, alcohols (ethanol and buthanol), liquefied natural gas, and liquefied hydrogen were analysed. Apart from synthetic jet fuels (FT and HEFA fuels), no listed fuel option is compatible with the current fleet of aircraft, requiring new airport infrastructure to support its use. For instance, hydrogen would have to be liquefied for its use in aviation. Hence, a new aircraft fleet would have to be designed for the use of cryogenic hydrogen. Furthermore, the development and commercialisation of large-scale production of biomass feedstocks, grown with a minimum arable land and freshwater, define the viability of synthetic jet fuels.

Although a large number of studies assess the environmental impacts and the techno-feasibility of aviation biofuels, very few considered social impacts related to alternative jet fuels. Wang et al. [12] assessed the social aspects of three potential biofuel supply chains in Brazil based on sugarcane, eucalyptus, and macauba, using a process-based approach with input–output analysis. Social indicators, such as employment, working conditions, labour rights, gender equity, and social development, were quantified. It was found that the three types of biofuels supply chains result in different levels of social effects. While the macauba-based biofuel has the highest economic value and generates the highest number of jobs, the eucalyptus-based biofuel offers more employment opportunities for women. Even though the macauba-based supply chain appears to perform the best, other social issues would need to be considered (e.g., human health and safety, livelihood, food security, energy security) to define the most favourable supply chain for biofuels.

5.2.2. Electrofuels

Alongside bio-based aviation fuels, the so-called e-fuels represent a promising option to cope with the fast growth in global air traffic and reduce its environmental footprint, with significantly lower land requirements in comparison with biofuels. By using renewable energy, water, and CO_2 captured from the air, a sustainable liquid fuel can be synthesised through the power-to-X (PtX) processes via electrolysis. Some potential aviation e-fuels are n-octane, methanol, methane, hydrogen, and ammonia. E-fuels can be either used with combustion, as conventional fuels, or in fuel cells, such as hydrogen [74].

The environmental viability of hydrogen in the aviation industry has been widely discussed in the literature, compared with conventional fossil-based jet fuel [52,53,69,75,76]. The use of hydrogen in aviation is becoming an attractive propulsion alternative due to its high energy content, zero CO_2 emissions associated with its use (only water vapour is emitted), and the possibility to be produced by electrolysis of water using renewable energy [52].

Schmidt et al. [53] review the state-of-art technologies for power-to-liquid (PtL) pathways, assessing its potential compared with fossil jet fuel. Results show that PtL fuel offers a viable option for the transition of the aviation sector from fossil to renewable fuel, using existing aircraft systems. It emits less GHG emissions than kerosene, and fewer resources (land and water) are required compared with biofuels. Furthermore, core technologies along the PtL route have achieved technological readiness for industrial large scale implementation, which is driven by the continued reduction in costs of hydrogen production via electrolysis powered by renewables.

A potential reduction in energy consumption by the use of liquid hydrogen and natural gas is evaluated by Pereira et al. [75] using a WTW approach. CO_2 emissions and local pollutants are also assessed for the calculation of environmental and social costs. In comparison with kerosene, hydrogen produced by electrolysis (with electricity from hydropower) can achieve a reduction of environmental costs of up to 60% and has a 19% better performance in terms of energy consumption. Even hydrogen produced from fossil energy sources shows a 13–21% reduction of environmental and social costs. On the other hand, the usage of hydrogen requires a larger tank volume and leads to cloud formation caused by water vapour emissions.

Additionally, Koroneos et al. [52] analyse the environmental impacts of production chains of hydrogen in comparison with kerosene for aviation, considering different impact categories under an LCA study. It was found that hydrogen from all production paths (from steam reforming of natural gas or different renewable sources) performs better than kerosene in terms of GWP. For example, considering an A319-100 aircraft type at a flight range of 3360 km, while kerosene is associated with 0.01 kg of life cycle CO_2 equivalent per kilometre travelled (kg CO_2 eq./km), hydrogen produced from RES presents 0.005 kg CO_2 eq./km, and also performs significantly better than natural gas (around 0.007 kg CO_2 eq./km). For the acidification effect, the benefit of all hydrogen paths against kerosene is even higher. The lowest environmental impact is shown by hydrogen produced by wind energy. Eutrophication and winter smog results are significantly better for all hydrogen types than for kerosene. Even though this study presents the attractiveness of hydrogen for aviation, it emphasises the relevance of the hydrogen production path on the associated environmental impacts.

According to Bicer and Dincer [76], even though hydrogen costs are higher in comparison with ammonia, methanol, and jet fuel, hydrogen-fueled aircraft perform better in terms of GHG emissions. The results for the GWP show a substantial reduction potential of around 70% compared with kerosene. Regarding land occupation and human toxicity potentials, hydrogen gives a significantly lower contribution [76]. However, the fuel production route, whether the conventional or the renewable-based method, plays an essential role in the assessment of environmental burdens, as the environmental impact can vary significantly, also among the different RES. Hydrogen production from geothermal energy performs best, followed by hydropower, wind, and photovoltaics as the worst option. Despite the necessary changes required to fulfil aviation fuel specifications, the fuel alternatives are attractive due to their long-term viability and environmental sustainability [76].

Next to the analysis of environmental indicators, fuel costs for the operation of an aircraft are determined. Bicer and Dincer [76] compute the average fuel costs of an aircraft based on fuel consumption (in kg/km) and the fuel costs (in US$/kg). From an economic perspective, fossil kerosene is the best option. The best alternative fuel is methanol, with a 38% higher fuel cost compared with kerosene. Hydrogen is not yet a worthwhile alternative to kerosene, as fuel costs are 85% higher. This is mainly due to the high production costs, which are 3.7 times higher than those of kerosene. From an economic point of view, ethanol is the most unattractive alternative fuel. The fuel costs are 136% higher compared with kerosene.

Hydrogen-powered aircraft were also analysed by Johanning and Scholz [69] under an LCA study for the aircraft's conceptual design. In comparison with a conventional aircraft, the results show increased environmental impacts of 300% higher (single score) or 157% higher when the electricity for electrolysis comes from RES, emphasising the role that background systems play in the sustainability assessment. The high environmental impact is explained by the high energy intensity of hydrogen production as well as cirrus cloud formation, which is caused by water vapour emissions and leads to increased RF. However, as already mentioned, environmental impacts can be reduced when adapting the flight altitudes, so that cloud formation is reduced.

5.2.3. Alternative Powertrains

Electrification of aircraft is also seen as a potential technology to reduce the environmental impact of aviation due to zero in-flight emissions [8]. However, the literature on sustainability assessment of electric aircraft is relatively scarce. Only two studies undertake analyses of electric propulsion of aircraft.

Ploetner et al. [8] conducted an LCA, focusing on GHG emissions of the Ce-liner, a conceptual fully-electric aircraft for the market entry year 2035. The impacts are calculated for an assumed flight distance of 1667 km. The results show that battery production leads to higher GHG emissions, which are compensated during flight operation. Again, different scenarios lead to the conclusion that the electricity source for the operation of the Ce-liner has a dominating influence on GHG emissions. With the estimated electricity mix in the year 2035, the Ce-liner is expected to lead to a 35% reduction in GHG emissions in comparison with a conventionally powered aircraft of the same size and operation characteristics. However, if the electricity comes from renewable sources, a higher reduction potential can be expected.

Johanning and Scholz [69] performed an LCA for the conceptual design of electric-powered aircraft. They found a 45% reduction of the environmental impact (single score results) compared with a conventionally powered reference aircraft. In the case of RES for the electricity used during the operation, the reduction might be as high as 95%. However, a direct comparison is not possible as the range of the electric aircraft is reduced by half compared with conventional aircraft due to the batteries' weight.

Hence, the potential impact reductions for battery-powered aircraft heavily depend on the source of electricity, specifically on the share of renewable energy. However, the expansion of renewable sources is not only critical for the aircraft operation stage but also for battery production. Due to energy-intensive battery manufacturing processes, a shift from the use stage to the production stage might occur. Additionally, due to the relatively low energy density of batteries, they are restricted to small aircraft with few passengers and over short distances, such as the eVTOLs. Furthermore, new aircraft designs, as well as new airport structures, are needed. Thus, challenges need to be overcome to increase the viability of electric aircraft.

Building upon this detailed literature analysis, research gaps are identified, and future research directions are underlined in the following section.

6. Research Gaps and Future Research Directions

The conducted literature analysis has shown that some aspects of the framework are already well addressed in the scientific literature. However, research needs are also identified. In the following section, the main findings of this article are discussed in order to answer the research questions defined in Section 2.

6.1. Data Models

Concerning multidisciplinary research environments, several MDA environments (e.g., [32,34–37]) have been developed. Although these environments provide a good basis for virtual product design and assessment, they are currently missing a direct link to sustainability assessment. The same is true for available common data models, such as CPACS. It already provides a profound basis for multidisciplinary and multilevel sharing of data in an engineering network. However, so far, it has not been linked to sustainability assessment methodologies, such as LCA, LCC, or SLCA. In addition, a more concrete recommendation on how to achieve effective data management structures and how to measure their effectiveness and the associated effort is lacking. This would require an integrated methodological framework to develop and implement data management structures for the engineering of aircraft systems and to analyse and assess its effectiveness concerning overarching aims, such as sustainability and energy efficiency.

6.2. Life Cycle Modelling and System Analysis

Concerning future technologies in aviation, alternative fuels are receiving particular attention. Their potential to reduce the environmental impact of aviation compared with fossil kerosene has been extensively investigated, considering the entire fuel life cycle, as analysed by Hileman [56] and Klein [60]. The main focus lies on the CO_2 reduction potential through various feedstocks and production processes, as investigated by Han et al. [59], Lokesh et al. [63], and Cox et al. [77]. Specific concerns regarding land-use change and food safety, attributed to the feedstock cultivation stage, have been addressed. Some authors also considered cost-related indicators (e.g., Crossin [67] or Collier et al. [71]). However, very few assessed the social impacts of biofuel production on workers and the local community aspects (e.g., Jagtap [73] and Wang et al. [12]). The need for further research, particularly on human health and safety, livelihood, energy security is identified, which would help to identify more sustainable supply chains for biofuels.

In addition to biofuels, reduction of environmental and economic impacts by the use of e-fuels has been analysed by Bicer and Dincer [76] and Koroneos et al. [52]. While the potential of hydrogen in reducing the GHG emissions is addressed, considering different production pathways, further research on other potential drop-in fuels, such as n-octane, is identified. Furthermore, economic impacts derived from modifications in aircraft design and infrastructure demand (energy-intensive processes, high temperature, high-pressure reactors, adequate storage facilities, etc.) for e-fuels synthesis through PtX technologies need further analysis. In addition, the assessment of the social aspects of e-fuels production is missing so far and should be addressed in the future.

Alongside e-fuels, battery-powered aircraft are analysed in a few articles (e.g., Johanning and Scholz [51] and Ploetner et al. [8]). As known from related industries, critical processes are involved in the extraction of raw materials for batteries, which has to be considered in the sustainability assessment. Further research on the impacts of production and EoL stage of electric aircraft need to be addressed, also exploring the impact of data uncertainty on the results.

Besides, economic and social aspects need to be integrated into the analysis. This includes assessing the performance of potential energy sources, their production, and supply. Moreover, no studies were found assessing fuel cell systems for aircraft within the scope of this paper. A particular need for research in this area is identified, including a comparison with hybrid configurations.

Looking at the different methods and tools for the sustainability assessment of emerging technologies in aviation, LCA is a well-known practice to assess their environmental implications. However, environmental indicators should be diversified, analysing beyond the reduction in GHG emissions. Besides quantifying the potential reduction on CO_2 emissions from the adoption of more sustainable technologies, further investigations on the impact of aircraft contrails on climate forcing by changing the altitude of the flight are needed. The influence of different battery technologies for aviation applications on the environmental impact is also unclear.

To quantify the economic impacts, analysis has often been carried out only as a supplement to a comprehensive environmental assessment, and usually, the economic indicator is considered in aggregated form. However, in order to examine economic aspects in greater depth, more comprehensive assessment approaches should be used (such as the LCC approach as described by Hunkeler et al. [78]), and frameworks for the economic analysis must be defined. Additionally, the choice of economic indicators should be considered more carefully in this context. While price- or revenue-oriented indicators are usually only relevant for individual stakeholder groups, indicators such as costs or value added of a product system along the life cycle provide a more comprehensive understanding. Besides, the value of the product system can be better quantified by the indicator value added.

Similarly, social indicators need to be chosen for the given context, identifying the most relevant ones for individual stakeholder groups. The SLCA approach, as defined by UNEP/SETAC [25], for emerging technologies in aviation is almost entirely lacking, needing to be carried out in order to identify and analyse potential social problem shifting. On this basis, a framework for the socio-economic sustainability assessment of emerging aircraft technologies should be developed, which allows a comprehensive economic and social analysis. By adding more detailed economic and social analyses to the environmental analysis, a more comprehensive sustainability assessment can be made possible.

Finally, in order to fill these research gaps and support a robust evaluation of future technologies in aviation, an integrated LCE modelling approach, as proposed in Section 2, is needed. This will enable a better understanding of the environmental, economic, and social implications of emerging technologies by combining different context scenarios and studying the interactions between different designs, product parameters, and spatial differences. Considering that the variability of future technologies concerning geographic, technical, and temporal aspects will increase, the analysis will become much more complicated. The risk of problem shifting will increase so that the introduced framework and guidelines are needed to develop models and tools that support decision-making for the future of aviation.

7. Conclusions and Outlook

The transition towards more sustainable and energy-efficient aviation is strongly related to a diversification of technologies with the potential to overcome environmental challenges currently faced by the aviation sector. Technological developments are occurring, especially regarding alternative powertrains. New alternatives to jet engines powered by fossil kerosene, such as propulsion systems based on batteries and fuel cells, e-fuels, and biofuels, are coming up. Although these technologies can bring solutions for reducing aviation emissions, new environmental and socio-economic challenges might also be associated with them.

In this paper, a framework for the modelling and sustainability assessment of future technologies for more sustainable and energy-efficient aviation is introduced. By conducting a structured literature analysis, already well-addressed aspects of the framework within the scientific literature were identified, and further need for research was determined.

Regarding data models for modelling the foreground and background systems, a wide variety of studies is available. Models such as CPACS provide good support basis for virtual product design. However, a direct link to the sustainability assessment is currently missing, especially to well-known methods for sustainability assessment, such as LCA, LCC, SLCA, or LCSA. A significant body of research has already been carried out for life cycle modelling and system analysis, dominated by alternative fuels. However, the need for further research in the field of modelling and assessing batteries and fuel cells in terms of environmental and socio-economic aspects has been highlighted. Models are needed to understand the implications of future aviation technologies beyond the use stage. The impact in the extraction of critical raw materials and the challenges in EoL stages still remains unclear.

Further research activities exploring beyond the reduction in GHG emissions with the adoption of new technologies is proposed, investigating the impact of aircraft contrails on climate forcing by changing the altitude of the flight. Additionally, to ensure a comprehensive sustainability assessment for the future development of aviation, not only socio-economic analyses need to be integrated to the LCA, but the relevant indicators need to be carefully identified in the given context. Further research activities towards exploring the scenarios under which battery-powered aircraft are more sustainable than hydrogen-powered fuel cell aircraft are needed.

With the introduced framework built upon the concept of integrated computational LCE, a large number of technologies and systems can be modelled with reduced effort, and high data uncertainty and variability of parameters can be handled. By integrating multi-scale physical and environmental, socio-economic models, optimization concerning the sustainability of future aircraft technologies can be done, investigating the scenarios under which a given technology would be more sustainable and energy-efficient. Hence, this approach can help engineers towards a more sustainable aircraft design and operation and contribute to improving the widespread applicability of the presented methodologies and tools in the aviation industry.

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